

CHAPTER 10

Coagulation¹

Introduction

Coagulation has historically been used for the control of particulates in drinking water, and its role in the simultaneous control of organic carbon is well known. With the inclusion of disinfection by-product (DBP) control as part of the Environmental Protection Agency's (EPA's) drinking water regulatory philosophy, the role of coagulation has expanded to include control of DBP precursors. This chapter presents recent studies conducted by the EPA's Office of Research and Development (ORD) in Cincinnati that (1) examined conventional coagulation and coagulation enhanced to more effectively control organic carbon and DBP precursors, and (2) examined the effects of enhanced coagulation on other water quality parameters.

Background

Water systems treating particulate-laden surface waters conventionally coagulate their waters to remove turbidity. Their goal is to achieve sufficiently low levels that downstream filters operate without excessive buildup of head loss (HL) and achieve cost-effective filter run times (FRTs). During conventional coagulation, the concentration of natural organic matter (NOM) is lowered. Since DBP precursors are part of the NOM, a strategy for control of DBP formation is removal of the NOM by coagulation prior to disinfection. Because the NOM is largely unidentified and not directly measurable, total organic carbon (TOC) serves as a surrogate for the DBP precursors. Typically, about 90 percent of the TOC is dissolved organic carbon (DOC); the other 10 percent is sorbed onto particulates. There are surface waters, however, for which the DOC is a lower percentage of the total.

Aluminum and iron salts are typically used for coagulation. For metal salts, two mechanisms for removal of NOM are accepted (Singer and Harrington 1993; Krasner and Amy 1995; Owen et al. 1993). In the first, negatively charged NOM is neutralized by positively charged metals forming insoluble complexes (Al or Fe humates and fulvates), followed by precipitation of NOM with the floc. In the second, NOM adsorbs onto metal hydroxide (Al(OH)₃ floc or Fe(OH)₃ floc) precipitates. The effectiveness of coagulation is strongly dependent on pH and the dose of the coagulant. At higher coagulant doses, more metal for floc or complex formation is available. Typically, coagulation of NOM is most effective in the pH range of 5 to 6, as charge neutralization tends to be more effective at lower pH. At lower pH, the charge density of humic and fulvic acids is reduced, making them more hydrophobic and adsorbable. Lower pH can be achieved by acidification and/or by higher coagulant dosing. More metal hydroxide (Al(OH)₃ or Fe(OH)₃) is formed at higher coagulant doses, therefore more H⁺ in solution lowers the pH. Thus, TOC removal and DBP precursor removal can be enhanced by decreasing pH and/or by increasing coagulants doses.

NOM can be divided into hydrophobic and hydrophilic fractions (Singer and Harrington 1993). The hydrophobic fraction tends to be less soluble, higher molecular weight, and more aromatic and is described as humic. The hydrophilic fraction is described as non-humic. The humic (hydrophobic) fraction is that retained on XAD[®] resin. The non-humic (hydrophilic) fraction passes XAD[®] resin. The humic fraction is more readily coagulated by aluminum and iron salts than the non-humic fraction.

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Table 10-1. Required Percent Removal of TOC by Enhanced Coagulation (Federal Register 1998)

Source Water TOC, mg/L	Source Water Alkalinity, mg CaCO ₃ /L		
	0 to 60	>60 to 120	>120
>2.0 to 4.0	35	25	15
>4.0 to 8.0	45	35	25
>8.0	50	40	30

Ultraviolet absorbance (UVA) is caused by aromatic and unsaturated double bonds in the NOM and is commonly measured at 254 nm (UV254). Specific UVA (SUVA), or UV254 divided by DOC, is an indicator of the DBP precursor removal treatability (Federal Register 1998). Edzwald (1993) has shown that SUVA in the 4 to 5 L/mg-m range is characteristic of waters with humic (hydrophobic) carbon and is more easily coagulable for DOC control, whereas SUVA in the <3 L/mg-m range is characteristic of waters with non-humic (hydrophilic) carbon, which is less susceptible to DOC removal by coagulation.

Enhanced coagulation has two places in the Disinfectant/Disinfection By-Product (D/DBP) Rule. One is as a treatment technique for the control of precursors for identified and nonidentified DBPs. Another is as a best available technology (BAT) for the control of regulated total trihalomethanes (TTHMs) and five regulated haloacetic acids (HAA5).

As a treatment technique, water systems are not expected to optimize, or maximize, the removal of DBP precursors. Whether coagulation is enhanced or optimized for the control of DBP precursors is a matter of degree. So as not to be cost prohibitive, systems must meet target percent removals of TOC where TOC serves as a surrogate for the identified and nonidentified DBP precursors. The targets are based on two factors, the source water's TOC concentration and the source water's alkalinity. A 3 × 3 matrix results and is shown in Table 10-1 (Federal Register 1998). The table reflects two observed phenomena: relatively more TOC can be removed from higher-TOC waters than from lower-TOC waters, and lower percent removal of TOC is expected in higher-alkalinity waters as higher alkalinity makes depressing the pH more difficult.

Meeting the requirements of the 3 × 3 matrix is termed Step 1 in the D/DBP Rule. Systems may meet these requirements however they choose; enhancing coagulation is an option, as is the use of granular activated carbon, powdered activated carbon, etc.

As stated, the purpose of the TOC removal in the Step 1 matrix is control of precursors for identified and nonidentified DBPs. Systems with good control of DBPs do not have to meet the matrix requirements, i.e., there are alternative compliance criteria to Step 1. These are based on other water quality measures indicative of control of DBP precursors and include: source water TOC < 2.0 mg/L, treated water TOC < 2.0 mg/L, TTHM not > 40 ug/L and HAA5 not > 30 ug/L with the use of chlorine, source water SUVA ≤ 2.0 L/mg-m, and finished water SUVA ≤ 2.0 L/mg-m.

Meeting the requirements of the 3 × 3 matrix is thought to be achievable by 90 percent of drinking water systems, and these systems would realize an incremental improvement in DBP precursor over their conventional practices (Federal Register 1998). Some systems are likely to already meet Step 1 requirements with conventional coagulation (Krasner and Amy 1995).

If systems can not meet the Step 1 criteria because of the nature of their precursor, they must perform jar tests to determine how much TOC removal can be achieved, i.e., they must define alternative performance criteria. This is termed Step 2. The D/DBP Rule will force many water systems to move from conventional to enhanced coagulation and to expand their coagulation objectives to include TOC removal.

Conventional vs. Enhanced vs. Optimized Coagulation

Figure 10-1 describes the results of adding alum to move from conventional coagulation (achieving the target percent removal of TOC) to coagulation optimized for the removal of TOC. It represents jar testing of 4 waters: Great Miami River (GMR), East Fork Lake (EFL), Miami Whitewater Lake (MWL), and Stonelick Lake (SL) (Miltner et al. 1994a). Alum doses to control turbidity ranged from as low as 15 mg/L to as high as 45 mg/L as indicated by the conventional box in the figure. Control of turbidity in jar testing was defined as achieving 1 nephelometric turbidity unit (NTU) in settled waters. Jar tested waters consistently resulted in lower settled turbidities than pilot-treated waters; based on these and other studies (Miltner et al. 1994b), jar test settled turbidities near 1 NTU resulted in pilot plant settled turbidities near 2 NTU. At the other extreme, doses to achieve optimized removal of TOC ranged from 75 to 130 mg/L as indicated by the optimum box in Figure 10-1. Optimized coagulation was defined as the lowest coagulant dose resulting in the best removal of TOC. An

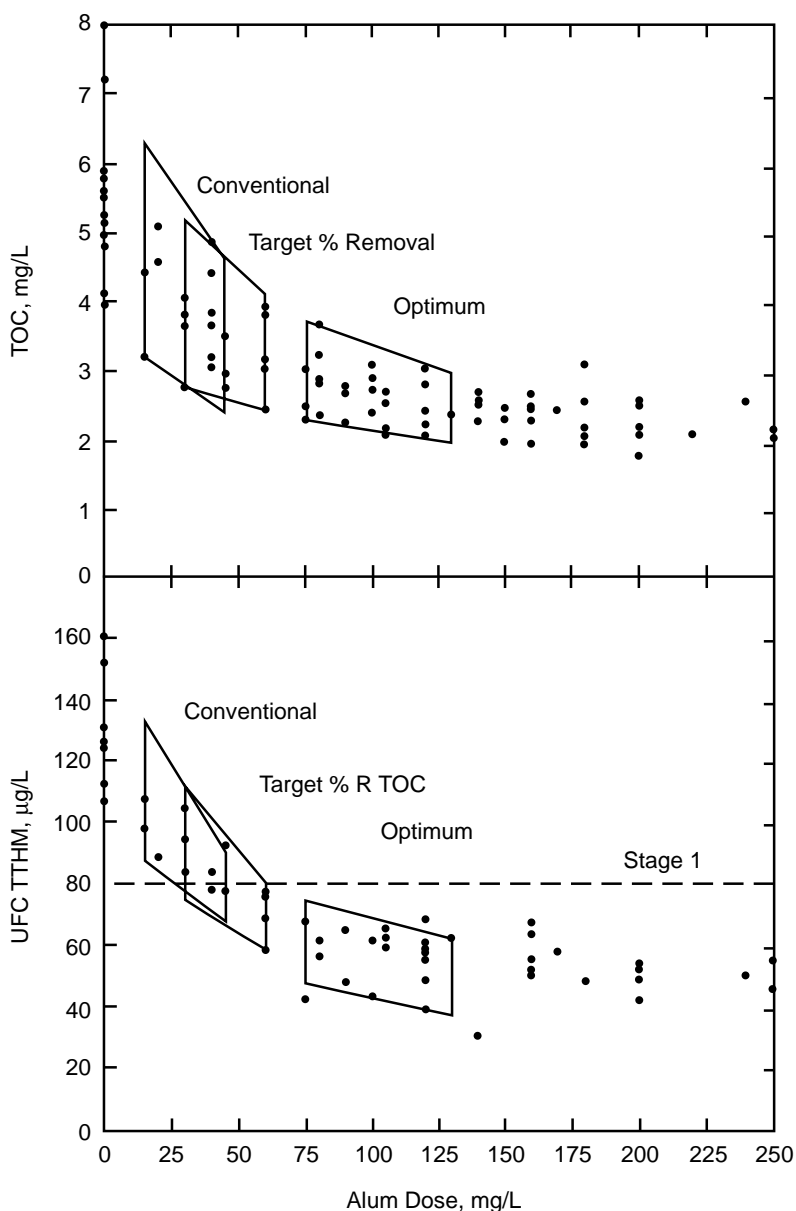


Figure 10-1. Control of TOC and UFC TTHM in GMR, EFL, MWL, and SL waters by coagulation (Miltner et al. 1994a).

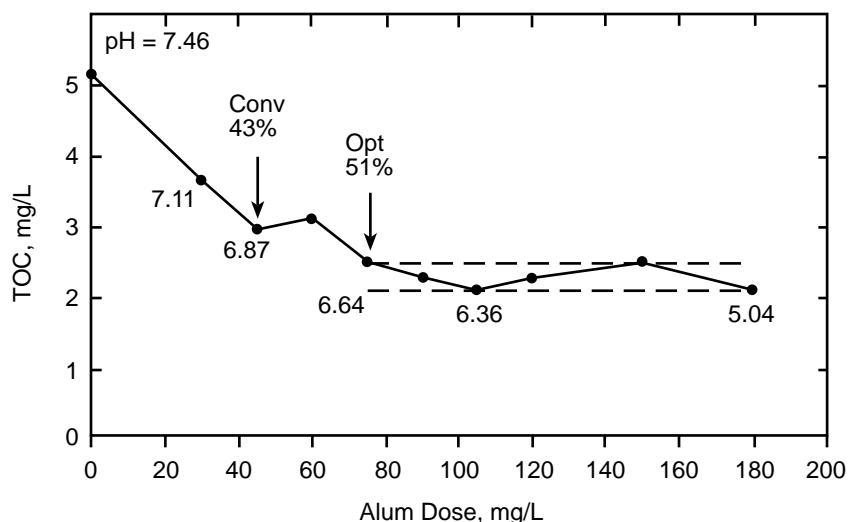


Figure 10-2. Control of TOC in EFL water by alum coagulation (Miltner et al. 1994a).

example is given in Figure 10-2 where 75 mg/L alum resulted in 51 percent removal of TOC; at higher doses, TOC concentrations could not be differentiated. Alum doses required to meet the requirements of enhanced coagulation ranged from 30 to 60 mg/L as indicated by the target % R TOC box in Figure 10-1. These results indicate that enhanced coagulation could be achieved at doses below those required to optimize TOC removal and at doses not significantly greater than those required to control turbidity. In some cases, conventional treatment alone was sufficient to meet the requirements of enhanced coagulation as indicated by the overlap of the conventional and target % R TOC boxes. These data support the intentions of the D/DBP Rule, wherein 90 percent of systems would be able to meet the requirements of enhanced coagulation with moderate changes to conventional coagulation.

Figure 10-1 also shows similar data for control of TTHM precursors. Precursors in this chapter were assessed by chlorination under uniform formation conditions (UFCs) (Summers et al. 1996). UFCs represent national, mean, finished-water, distribution-system conditions of 1 mg/L free chlorine after 24 hours at pH 8 at 20 C. Because they are distribution-system conditions, the DBP concentrations represent those reaching the consumer. When control of TTHM is considered for these four waters, conventional coagulation rarely produced TTHM concentrations below the D/DBP Rule Stage 1 maximum contaminant level (MCL) of 0.080 mg/L. Enhancing coagulation to meet the target percent removals of TOC generally resulted in TTHM concentrations below the Stage 1 MCL. In Figure 10-1, 30 mg/L represents only the lowest alum dose that achieved the target percent removal of TOC, i.e., it represents only one water on one date. Optimizing coagulation for TOC control always resulted in Stage 1 MCL compliance. Similar results were obtained for HAA5 and its Stage 1 MCL of 0.060 mg/L. This supports the basis of enhanced coagulation's place in the D/DBP Rule. As a BAT, enhanced coagulation can result in the control of TTHM and HAA5.

Enhanced Coagulation's Role in Water Quality

Ohio River (OR), Green Swamp (GS) (Dryfuse et al. 1995), MWL, and EFL waters (Miltner et al. 1994a) were jar tested to assess the relationships between TOC, SUVA, chlorine demand, and precursors for total organic halide (TOX), TTHM, six haloacetic acids (HAA6), chloral hydrate (CH), four haloacetonitriles (HAN4) and chloropicrin (CP). Results are given in Table 10-2. The data show that conventional coagulation would not meet the requirements of the 3 × 3 matrix for TOC removal in OR and MWL waters and that additional treatment processes, enhanced coagulation or others, would be

required. Conventional coagulation would meet the requirements, however, in EFL and GS waters. Several trends are apparent in the results presented in Table 10-2. These trends are also apparent in Table 10-3.

Improved Water Quality with Enhanced Coagulation

Moving from conventional coagulation to coagulation optimized for the removal of TOC results in improved removal of precursors for TTHM, HAA6, CH, HAN4, CP, and the surrogate TOX and in reduction in chlorine demand. Using coagulation of MWL water as an example, optimized coagulation was better than conventional coagulation for all parameters. Based on the relationship between conventional, enhanced, and optimized coagulation described in Figure 10-2, moving from conventional coagulation to enhanced coagulation would result in improved removal of DBP precursors and reduction in chlorine demand, but to a lesser degree than moving to optimized coagulation.

Table 10-2. Coagulation of OR, MWL, EFL and GS Waters with Alum

Parameter	Percent Removal							
	OR		MWL		EFL		GS	
	(Dryfuse et al. 1995)		(Miltner et al. 1994a)		(Miltner et al. 1994a)		(Dryfuse et al. 1995)	
	DOC = 2.47 mg/L		TOC = 4.79 mg/L		TOC = 5.16 mg/L		DOC = 15.3 mg/L	
	Alkalinity = 59 mg/L		Alkalinity = 104 mg/L		Alkalinity = 80 mg/L		Alkalinity = 88 mg/L	
	TOC Target = 35% R		TOC Target = 35% R		TOC Target = 35% R		TOC Target = 40% R	
	UV254 = 0.05/cm		UV254 = 0.092/cm		UV254 = 0.19/cm		UV254 = 0.73/cm	
	SUVA = 2.02 L/mg-m		SUVA = 1.92 L/mg-m		SUVA = 3.70 L/mg-m		SUVA = 4.77 L/mg-m	
	Conv	Opt	Conv	Opt	Conv	Opt	Conv	Opt
TOC, DOC	20	46	18	45	43	51	47	71
UV254	20	60	32	54	68	74	67	86
SUVA	0	26	16	17	43	47	38	53
UFC TOX	30	63	36	60	57	73	70	86
UFC TTHM	18	59	16	49	53	74	60	83
UFC HAA6	36	67	44	71	66	79	70	90
UFC CH			22	56	59	72		
UFC HAN4			30	46	45	52		
UFC CP			34	61	43	61		
Cl ₂ demand			37	61	53	50		

Table 10-3. Coagulation of GMR Water with Alum and Ferric Chloride (Miltner et al. 1994a)

Parameter	Percent Removal			
	Alum		Ferric Chloride	
	Conventional	Optimized	Conventional	Optimized
TOC	22	45	25	54
UFC TOX	9	44	23	51
UFC TTHM	13	46	25	54
UFC HAA6	10	61	31	64
UFC CH	30	66	41	73
UFC HAN4	25	40	26	44
UFC CP	39	44	61	78
Cl ₂ demand	50	67	49	58
pH	7.92	7.04	7.85	6.91
Coagulant dose, mg/L	15	120	20	125

TOC as an Indicator of DBP Precursor Control

Coagulation to remove TOC results in the removal of the precursors for THMs, HAAs, CH, HANs, CP, and the surrogate TOX, and the removal of TOC is generally a conservative indicator of the removal of these DBP precursors. Using conventional coagulation of EFL water as an example, TOC removal was 43 percent, whereas removal of TTHM, HAA6, CH, HAN4, CP, and TOX precursors ranged from 43 to 66 percent. This supports the basis of enhanced coagulation's place in the D/DBP Rule. As a treatment technique, enhanced coagulation to remove TOC can result in the removal of precursors for numerous DBPs. As a BAT, enhanced coagulation can result in the control of TTHM and HAA5.

Better Removal of TOC in Higher-TOC Waters

Raw waters higher in TOC tend to have higher percent removals of TOC. OR water with a raw TOC of 2.47 mg/L achieved an optimum TOC removal of 46 percent, whereas GS water with a raw TOC of 15.3 mg/L achieved 71 percent removal. This is consistent with the pattern in the 3 × 3 enhanced coagulation matrix (Table 10-1) in which higher-TOC waters are targeted for higher percent removal of TOC.

SUVA as an Indicator of DBP Precursor Control

Raw waters higher in SUVA tend to have higher percent removals of DBP precursors. OR and MWL waters with SUVAs near 2 L/mg-m achieved 60 to 63 percent removal of precursors for the DBP surrogate TOX when coagulation was optimized for TOC removal. EFL water with a SUVA of 3.70 L/mg-m achieved 73 percent and GS water with a SUVA of 4.77 L/mg-m achieved 86 percent. Precursors for TTHM and HAA6 generally followed the same trend. This is consistent with SUVA's use in the D/DBP Rule as an indicator of DBP precursor treatability.

Coagulation With and Without Acid Addition

Systems may opt to achieve the lower pH of enhanced coagulation by increasing the coagulant dose and/or by adding an acid. Tryby et al. (1993) studied acid addition in jar testing of OR water. Figure 10-3 shows TOC control in an alum-treated water of ambient pH and an alum-treated water with pH

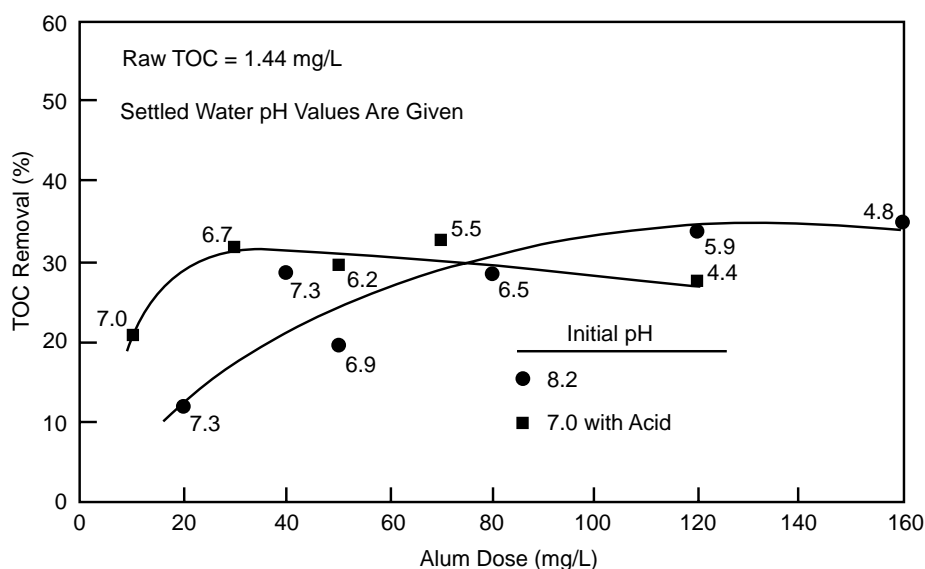


Figure 10-3. Control of TOC in OR water by alum coagulation (Tryby et al. 1993).

adjusted to 7 with hydrochloric acid. In each case, about 34 percent optimal removal of TOC was achieved. Without acid addition, 120 mg/L alum was required to achieve optimum TOC removal at pH 5.9. With acid addition, only 30 mg/L alum was required to achieve optimum TOC removal at pH 6.7. Each system attempting to enhance coagulation could decide on acid addition vs. additional coagulant based on factors such as safety, chemical handling, sludge production and handling, and costs.

Comparing Alum and Iron Coagulation

Table 10-3 and Figure 10-4 show jar testing results in which GMR water coagulated with ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) gave somewhat better removal of TOC and DBP precursors than when alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$) coagulated (Miltner et al. 1994a). The exception was in the control of chlorine demand. This may be affected by the reaction between iron and chlorine in meeting the UFC requirement of a 1 mg/L free chlorine residual.

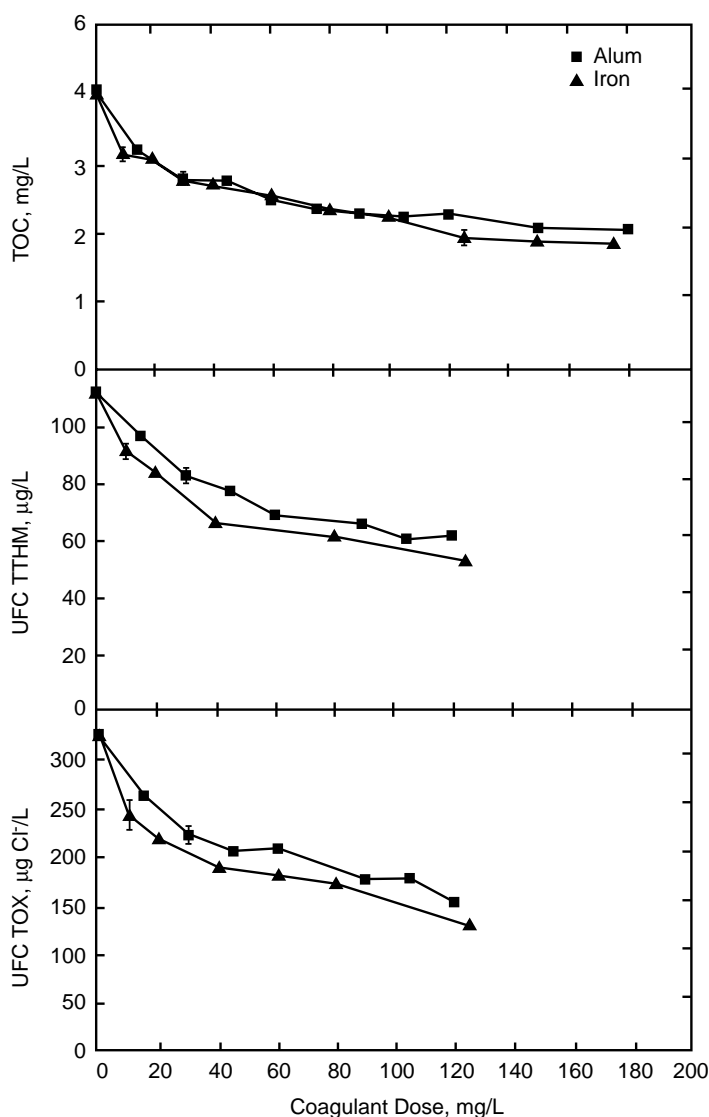


Figure 10-4. Control of TOC and DBP Precursors in GMR Water by Alum and Iron Coagulation (Miltner et al. 1994a).

The lower pH that occurs with iron at a given coagulant dose may explain, in part, the better performance of iron compared to alum. These data must be viewed with caution, however, as they are presented on a weight basis. When doses are compared on an equivalence basis, the advantage of treating with ferric chloride is offset as the ferric chloride curves in Figure 10-4 shift to the right about 9 percent, i.e., an 81.9 mg/L dose of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ is equivalent to a 90 mg/L dose of $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$. A system's choice of a coagulant should be based not only on treatment effectiveness but also based on factors such as cost, chemical handling, and sludge production and handling.

Table 10-3 also shows data similar to that in Table 10-2, i.e., improving coagulation to better control TOC results in improved control of precursors for TTHM, HAA6, CH, HAN4, CP, and the surrogate TOX.

Fractionation

Dryfuse et al. (1995) studied OR, EFL, and GS waters for the effects of coagulation on humic and non-humic fractions of DOC and on molecular-sized fractions of DOC. Raw and coagulated jar tested waters were examined before (in bulk) and after fractionation. Both conventional coagulation and coagulation optimized for DOC removal were employed. Waters were fractionated by XAD-8 resin to isolate the non-humic (hydrophilic) fraction in the resin column effluent. The humic (hydrophobic) fraction was determined by difference. Waters were separated by two parallel ultrafiltration membranes into <0.5K and <3K molecular size (MS) ranges. Thus, by difference, <0.5K, 0.5K–3K, and >3K MS ranges were determined.

Results for OR and GS bulk (unfractionated) waters are presented in Table 10-2 and show that DBP precursor removal, as measured by TOX, TTHM, and HAA6, was improved as the coagulant dose was increased from conventional to that optimized for DOC control.

Most of the DOC and the DBP precursors were in the larger molecular size (>0.5K) range. This is described in Table 10-4 in which the fractions represent the mean of the three raw waters. Similarly, most of the DOC and the DBP precursors were in the humic fraction.

Table 10-4. Molecular Size and H/NH Fractions of OR, EFL, and GS Raw Waters (Taken from Dryfuse et al. 1995; Dryfuse 1995)

Parameter	Percent of Total			Percent of Total	
	>3K	0.5K–3K	<0.5K	H	NH
DOC	34	45	20	53	47
UFC TOX	53	42	5	68	32
UFC TTHM	33	53	14	67	33
UFC HAA6	44	46	10	73	27

H = humic; NH = non-humic.

The effect of coagulation on MS fractions is seen in Table 10-5 and represents the mean of the three waters. The behavior of the DOC fractions was similar to that of the DBP precursor fractions. Conventional coagulation removed a greater percentage of the >3K MS fraction (61 to 86 percent) than of the smaller-sized fractions (9 to 45 percent). Optimizing coagulation brought about a small improvement in the >3K MS range, i.e., a 0 to 14 percent increase. The greatest improvement with optimized coagulation, however, was in the 0.5K–3K MS range where increases ranged 39 to 49 percent. Improvement in the <0.5 MS range was small, i.e., 0 to 13 percent.

Table 10-6 describes the effect of coagulation on humic and non-humic fractions for the mean of the three waters. The behavior of the DOC fractions was similar to that of the DBP precursor fractions. Conventional coagulation removed a greater percentage of the humic fraction (51 to 62 percent) than of

Table 10-5. Effect of Coagulation on Molecular-Sized Fractions of OR, EFL, and GS Waters (Taken from Dryfuse et al. 1995; Dryfuse 1995)

Percent Removal			
MS Fraction	DOC Conventional	DOC Optimized	Increase
>3K	81	86	5
0.5K–3K	9	49	40
<0.5K	16	26	10
	UFC TOX Conventional	UFC TOX Optimized	Increase
>3K	85	99	14
0.5K–3K	33	72	39
<0.5K	40	41	1
	UFC TTHM Conventional	UFC TTHM Optimized	Increase
>3K	61	61	0
0.5K–3K	22	63	41
<0.5K	45	45	0
	UFC HAA6 Conventional	UFC HAA6 Optimized	Increase
>3K	86	98	12
0.5K–3K	26	75	49
<0.5K	31	44	13

Table 10-6. Effect of Coagulation on H/NH Fractions of OR, EFL and GS Waters (Taken from Dryfuse et al. 1995; Dryfuse 1995)

		Percent Removal	
H/NH Fraction	DOC Conventional	DOC Optimized	Increase
H	51	72	21
NH	18	40	22
	UFC TOX Conventional	UFC TOX Optimized	Increase
H	52	83	31
NH	41	62	21
	UFC HAA6 Conventional	UFC HAA6 Optimized	Increase
H	62	86	20
NH	42	66	24

H = humic; NH = non-humic.

the non-humic fraction (18 to 42 percent). Optimizing coagulation brought about similar improvement in the removal of both fractions, i.e., 20 to 31 percent for the humic fraction and 21 to 24 percent for the non-humic fraction.

Speciation

Coagulation shifts the distribution of DBPs toward the more brominated species when enhanced or optimized coagulation is practiced. Table 10-7 shows TOC concentrations in parallel pilot plants treating EFL water and employing conventional coagulation and coagulation optimized for TOC control (Miltner 1994b). The precursor concentrations for TTHM and HAA6 formation are also shown in Table 10-7. Comparing conventional and optimized coagulation indicates improved removal of these precursors with optimized coagulation. Although the concentrations of THMs and HAAs that would form in post-disinfected water decreased with coagulation, both on a weight basis and on a molar basis, the percentage of brominated species increased as indicated by the ratios of brominated-to-total DBPs.

Table 10-7. Effect of Alum Coagulation of Pilot Plant-Treated EFL Water on DBP Speciation (Miltner et al. 1994b)

	TOC mg/L	UFC TTHM ug/L	UFC TTHM umole/L	UFC TTHM-Br umole/L	Ratio TTHM-Br:TTHM
Raw	4.81	102	0.814	0.079	0.097
Conv. settled	3.42	79	0.620	0.072	0.117
Opt. settled	2.21	53	0.424	0.064	0.150
	TOC mg/L	UFC HAA6 ug/L	UFC HAA6 umole/L	UFC HAA6-Br umole/L	Ratio HAA6-Br:HAA6
Raw	4.81	115	0.794	0.0133	0.017
Conv. settled	3.42	65	0.447	0.0126	0.028
Opt. settled	2.21	30	0.216	0.0111	0.051

Table 10-8. Comparison of Jar Testing and Pilot-Plant Treatment of EFL Water (Miltner et al. 1994b)

	Percent Removal			
	Conventional Coagulation		Optimized Coagulation	
	Jar Test ^a	Pilot Plant ^b	Jar Test ^a	Pilot Plant ^b
TOC	26	29	52	54
UV254	42	39	65	64
UFC TOX	22	24	41	47
UFC TTHM	46	44	73	73
UFC HAA6	38	36	61	63
Alum dose, mg/L	40	44	130	152
Turbidity, NTU	0.47	0.99	0.37	0.73
pH	7.23	7.34	6.50	6.57

^a Based on September 14 jar test.

^b Mean of six sample days from September 2 to September 14.

For example, optimized coagulation lowered TTHM precursors from 79 to 53 ug/L compared to conventional coagulation. With post-disinfection, however, about 15 percent, on a molar basis, of the 53 ug/L resulting from optimized treatment was brominated THMs, while only about 12 percent of the 79 ug/L resulting from conventional treatment was brominated THMs. As the precursor compounds were removed by coagulation, the bromide was unaffected. Thus, the bromide-to-organic carbon ratio increased, resulting in a higher percentage of the DBPs as brominated compounds when chlorinated under UFCs. Tryby et al. (1993) reported the similar trends with jar testing of OR water.

Scale Up

A concern of the Step 2 jar testing procedure, to define alternate performance criteria for enhanced coagulation, is scale-up reliability. Table 10-8 compares conventional and TOC-optimized coagulation for both jar testing and pilot-scale treatment of EFL water (Miltner et al. 1994b). The jar test was a good predictor of pilot-scale performance, with the exception of turbidity; jar test settled NTUs were about half the pilot-plant settled NTUs. These data suggest that if the coagulant mixing intensities (GT values) for the larger and smaller systems are similar (as they were in this study) and if the tests at both scales are conducted at close to the same time (the water qualities are similar), then jar tests will predict results from the pilot-scale system.

Secondary Effects

Two concerns with modifying coagulation to better control DBPs are (1) loss of control of microbial, particulate, or inorganic water quality parameters, and (2) operational problems. Several studies of the secondary effects of enhanced or optimized coagulation suggest no detrimental tradeoffs with regard to water quality, but increased sludge and resulting increases in cost.

Bacteria

Lytle et al. (1994) monitored heterotrophic plate count (HPC) bacteria (using R2A media) and total coliform (TC) bacteria through pilot plants treating EFL water using conventional and TOC-optimized coagulation. TOC-optimized coagulation resulted in a 0.54 log increase in removal of HPC bacteria and a 0.34 log increase in removal of TC bacteria.

Cryptosporidium Oocysts and Giardia Cysts

In the same study, Lytle et al. (1994) monitored particle counts in the size range of *Cryptosporidium* oocysts (3.1 to 7.0 μ m) and *Giardia* cysts (8.2 to 13.2 μ m). TOC-optimized coagulation resulted in 0.77 log better removal of *Cryptosporidium* oocyst-sized particles (1.88 vs. 1.11 logs) and 0.80 log better removal of *Giardia* cyst-sized particles (1.79 vs. 0.99 logs) as compared to conventional coagulation.

Ollier et al. (1997) studied the secondary effects of conventional, enhanced, and optimized coagulation in *Cryptosporidium parvum* oocyst-spiked OR, EFL, and Mississippi River (MR) waters. In addition to turbidity and oocysts, they monitored indigenous bacterial endospores (Rice et al. 1996) and total particle count (TPC) as indicators of oocyst removal efficiency. Several coagulation conditions were examined: conventional targeting 5 NTU, conventional targeting 2 NTU, enhanced following the requirements of the regulatory 3×3 matrix, optimized for TPC removal, and optimized for TOC removal. Table 10-9 summarizes results for the three waters.

These data suggest that systems that increase the coagulant dose to move from conventional to enhanced coagulation would realize improved removal of *C. parvum* oocysts and that endospores and TPC would be reasonable and conservative indicators of oocyst removal.

Table 10-9. Control of Microbes and Particulates by Coagulation of OR, EFL, and MR Waters (Ollier et al. 1997)

Parameter	Mean Log Removal				
	Conv-5	Conv-2	Enhanced	Opt-TPC	Opt-TOC
<i>C. parvum</i> Oocysts	1.3	2.0	2.6	3.3	3.0
Endospores	1.5	2.1	2.4	2.8	2.7
TPC	1.4	1.8	2.1	2.5	2.4
Turbidity	1.5	1.6	1.8	1.8	1.5
n	2	5	5	5	5
Mean alum dose, mg/L	20	36	45	67	112

Turbidity and Particles

Systems that increase the coagulant dose beyond that required by the 3×3 regulatory matrix would realize improved removal of *C. parvum* oocysts, endospores, and TPC through the coagulant dose range that optimizes TPC control. As shown in Table 10-9, optimizing for TOC control resulted in

Table 10-10. Effects of Treatment on Pilot-Scale Filter Operation and Mean Water Quality of EFL Water (Lytle et al. 1994)

Parameter	Conventional Coagulation	Optimized Coagulation	
	Filter 1 Ambient pH	Filter 2 Ambient pH	Filter 3 pH 8
Change in pH	7.37 to 7.47 + 0.10	6.88 to 6.90 + 0.22	6.68 to 7.95 + 1.27
Change in TPC/mL	18,207 to 2938 15,269	6027 to 205 5822	6027 to 300 5727
Change in Al ³⁺ , mg/L	0.648 to 0.080 0.568	0.472 to 0.025 ^a 0.447	0.472 to 0.291 0.181
HL buildup, cm/hr	8.89	3.60	1.45
FRT	shortest		longest

^a dissolved Al detection level = 0.025 mg/L

better removal of oocysts, endospores, and TPC than practicing enhanced coagulation. Optimizing for TOC control appeared to be destabilizing for particles since removal of oocysts and the other indicator parameters deteriorated beyond the coagulant dose range usually selected for optimized TPC control.

Aluminum, Particles, Head Loss, and Filter Run Time

Lytle et al. (1994) and Miltner et al. (1994b) reported on pilot-scale filter operation during parallel conventional and optimized coagulation of EFL water. Table 10-10 summarizes the results. The pH of coagulation and clarification in the optimized plant was lower (6.88) than in the conventional plant (7.37) because of the additional alum dose required in the optimized plant (see Table 10-8). Two parallel filters were operated in the optimized plant. Chlorine was applied ahead of all three filters in both plants to target UFCs. pH 8 was targeted in all three finished waters for UFCs. In Filters 1 and 2, pH was adjusted at the clear wells. In Filter 3, pH was adjusted to 8 at the filter. In this manner, the effects of pH and aluminum solubility on filter operation could be studied. The moderate pH changes in Filters 1 and 2 occurred because the liquid chlorine was basic.

Optimized coagulation removed more TPC than did conventional coagulation. As a result, the particle loading to Filters 2 and 3 was lower (6027/mL vs. 18,207/mL) and, consequently, the sludge production was higher in the optimized plant. The TPCs in the filter effluents in the optimized plant were approximately one log lower than in the conventional filter effluent (205/mL and 300/mL vs. 2938/mL).

Even though more aluminum was utilized in the optimized plant, more was precipitated. Thus, the dissolved aluminum loading to Filters 2 and 3 was lower (0.472 mg/L vs. 0.648 mg/L). Aluminum solubility increases with pH. Thus, the highest filter effluent dissolved aluminum was in Filter 3, which was adjusted to pH 8. In Filters 1 and 2, where pH was ambient, lower filter effluent dissolved aluminum occurred. Consequently, less aluminum precipitated in the optimized plant filters compared to the conventional plant filter (0.181 mg/L and 0.447 mg/L vs. 0.568 mg/L).

Table 10-10 shows that Filter 1, following conventional treatment, removed more particles and precipitated more aluminum than the other two filters. Consequently, it built up HL faster and had the shortest FRT. Conversely, with optimized treatment, HL buildup was slower and FRTs were longer.

This suggests that systems switching from conventional to enhanced coagulation may achieve more efficient filter operation. The tradeoff will be more sludge production because of the addition of more coagulant, or possibly a different type of sludge if enhanced coagulation was achieved by the addition

of an acid with the coagulant. These data also suggest that systems practicing enhanced coagulation should consider pH adjustment ahead of the filter to improve filter operation. The tradeoff will be higher dissolved aluminum entering their distribution systems.

Costs are always site specific. Because of the cost of additional coagulant or acid, the cost of sludge handling, and the cost of raising the pH to distribute water from plants practicing enhanced coagulation, the cost of water will likely be more expensive than from plants practicing conventional coagulation.

Summary

With the D/DBP Rule, many water systems will move from conventional to enhanced coagulation, expanding their coagulation objectives from turbidity removal to include TOC removal. Moving from conventional coagulation to enhanced coagulation to coagulation optimized for the removal of TOC results in improved removal of precursors for TTHM, HAA6, CH, HAN4, CP, the surrogate TOX, and chlorine demand. When coagulated, raw waters higher in SUVA and in TOC tend to have higher percent removals of DBP precursors. As a treatment technique, enhanced coagulation to remove TOC can result in the removal of precursors for these DBPs. As a BAT, enhanced coagulation can result in the control of TTHM and HAA5. Many systems should be able to meet the requirements of enhanced coagulation for TOC removal with moderate changes to conventional coagulation.

Although coagulation lowers the concentrations of DBP precursors, coagulation shifts the distribution of the DBPs formed by chlorination toward the more brominated species. This shift is even greater when enhanced or optimized coagulation is practiced.

Most DOC and DBP precursors are in the larger molecular size range, and most DOC and DBP precursors are in the humic fraction. Conventional coagulation removes a greater percentage of the >3K MS fraction than the smaller-sized fractions. Enhancing coagulation brings about small improvements in the >3K MS range and the <0.5 MS range; the greatest improvement with enhanced coagulation is in the 0.5K–3K MS range. Conventional coagulation removes a greater percentage of the humic fraction than the non-humic fraction. Enhancing coagulation brings about similar improvement in the removal of both fractions.

Moving from conventional to enhanced to TOC-optimized coagulation generally results in better control of HPC bacteria, TC bacteria, *C. parvum* oocysts, *Cryptosporidium* oocyst-sized particles, *Giardia* cyst-sized particles, TPC, and bacterial endospores.

Systems switching from conventional to enhanced coagulation may achieve longer FRTs. The tradeoff will be more sludge production. Systems practicing enhanced coagulation should consider pH adjustment ahead of the filter to achieve longer FRTs. The disadvantage of this practice when alum is the coagulant will be higher dissolved aluminum entering their distribution systems.

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